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Infiltration Experiment to Determine Vadose Zone Hydrologic Properties of a Stony Sediment Sequence Incorporating Geophysical Methods

Michael J. Thoma[1*]; Warren Barrash[1]; John Bradford[1]

[1] Center for Geophysical Investigation into the Shallow Subsurface; Boise State University, Boise, ID 83725

*michaelthoma@boisestate.edu

BOISE STATE UNIVERSITY

Center for Geophysical Investigation of the Shallow Subsurface

Abstract

A 5-day infiltration/recovery experiment was conducted in August 2011 at the Boise Hydrogeophysical Research Site (BHRS) to quantify variably-saturated flow behavior and parameterize moisture-tension-hydraulic conductivity relationships in an unconsolidated stony sediment sequence using hydrologic and geophysical methods. From geophysical monitoring and coring at the BHRS, we have identified a 5 m x 5 m x 2 m volume with consistent layered stratigraphy and have installed tensiometer nests and a neutron access tube to capture paired profile measurements of tension and moisture content in the vadose zone under natural conditions and during the test. Prior to the experiment, we used drilling logs, core samples, soil tension and moisture profiles, and ground-penetrating radar to determine 3D distribution and lithology of stratigraphic units. Grain-size distribution from core data, laboratory infiltration experiments on core sections, and inversion of tension and moisture response to natural rain events were used to estimate hydraulic properties, including van Genuchten parameters, porosity, and saturated hydraulic conductivity. Pre-test modeling with HYDRUS 1D was used to estimate "rain" application rate and duration required to reach steady-state and predict soil moisture / tension responses. Commercially available water misters were used to apply water over a 2 m by 5 m test area at a constant rate of ~1 cm/hr until steady-state, partially-saturated flow conditions were established through the entire 1.5 m vadose zone. After reaching steady-state, recovery was monitored for 3 days. Wetting front migration during infiltration and soil moisture redistribution after infiltration were observed continuously through vertically distributed tension and moisture measurements and with 3D ERT and 2D multi-offset GPR measurements. Temperature of the incoming water and soil temperature at the tensiometers was also measured. We present test results from both hydrologic and geophysical data and results from modeling soil moisture and tension distribution during the entire test including parameterization of moisture – tension – hydraulic conductivity relationships associated with paired moisture – tension states of the different stratigraphic units in these stony sediments.

Background and Site Description

- Fluvial gravel bar located approximately 16 km east of the city of Boise, ID (figure 1)
  - Aquifer is composed of unconsolidated sand and gravel/cobbles
  - The aquifer is approx. 20 m deep and contains distinct material zones[1]
  - Water table depths are generally 1 – 3 m BLS and are strongly controlled by stage in the adjacent Boise River
- The site contains 18 fully screened wells, 6 piezometers, 5 neutron access tubes for measuring soil moisture, and 3 tensiometers nest sets.
  - Each tensiometer set consists of a shallow nest with 5, and a deep nest with 4, vertically distributed tensiometers. All tensiometers are distributed between 2.5 – 0.4 m below land surface (BLS)
  - Tensiometer nest set TX5B and neutron tube NX5B were installed in spring 2011 for the purpose of recording soil tension during the planned infiltration experiment.

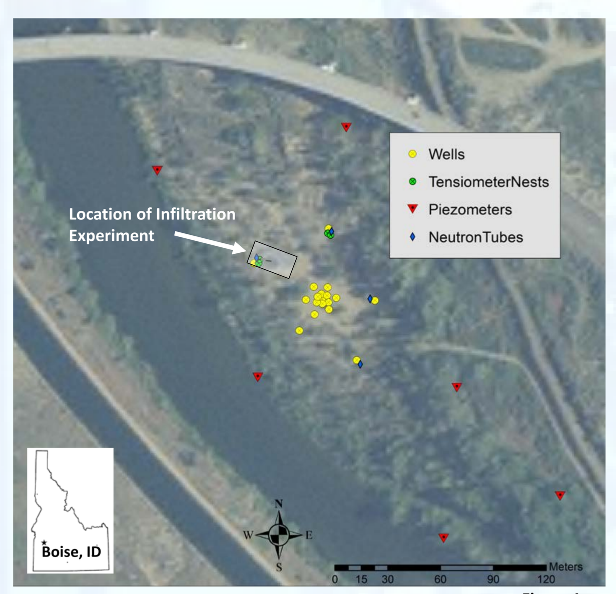

Figure 1

Rain Response and Pre-test Modeling

Tensiometer Rain Response

- Several intense rain events (rates > 0.2 cm/hr) where observed between 2010 and 2011 that had suitable duration and intensity to invoke a strong tension response in the originally emplaced tensiometer nests TX5AS and TX5AD (Figure 2)
  - These events were often accompanied by a temporary rise in the water table of a few centimeters observed by in-well transducers throughout the site
  - Tension responses from these events were used to estimate hydraulic parameters for the van Genuchten equation using a Monte-Carlo approach and HYDRUS 1D[2] (Table 1)

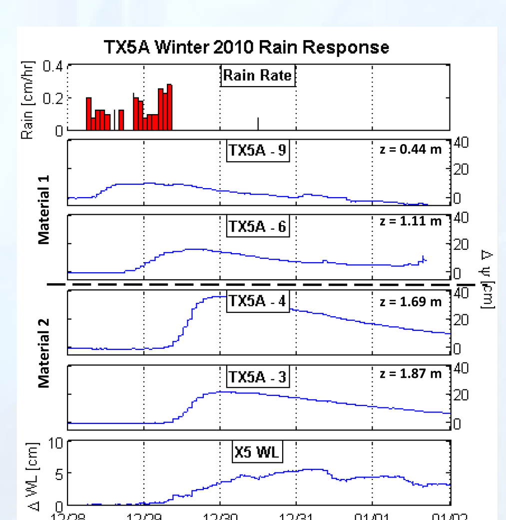

Figure 2

Table 1

TX5A Rain Response model results	Material 1	Material 2
θ_R [%]	0.044	0.047
θ_S [%]	0.28	0.25
α [1/cm]	0.18	0.22
n [-]	2.26	1.82
K_{sat} [cm/s]	0.143	0.104

2011 Installation

- During installation of TX5B, core data was collected at 45 cm (1.5 ft) intervals. These cores were sectioned and analyzed for grain size distribution
  - The majority of the cores fell into the typical material type of the BHRS (coarse sand/cobble) but at approximately 75 and 90 cm depth the material was distinctly more sandy (Figure 3)
  - To better predict the soil response to the infiltration test, this sandy section was reconstructed and used in a lab sprinkler test to estimate partially-saturated hydraulic properties by recording wetting from propagation (Table 2)
- Data from the rain response modeling, sandy core lab experiment, and 3D GPR were used to simulate the rain experiment prior to performing it in the field

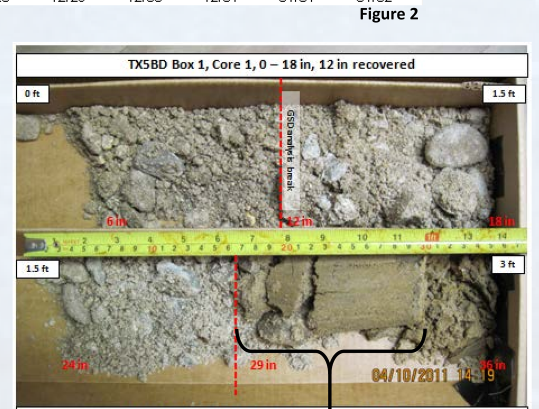

Figure 3

Results of Lab Rain Experiment on Fine Sand — Table 2

Parameter	θ_R [%]	θ_S [%]	α [1/cm]	n [-]	K_{sat} [cm/s]
Value	0.05	0.41	0.124	2.28	0.032

Test Setup and Performance

Test Setup

- Water was pumped from a nearby well using submersible GRUNDFOS pump
- "Rain" was applied using 66 commercial misters (max 0.5 gph) arranged over TX5B-NX5B installations (Figure 4) and measured using 4 calibrated tipping buckets
- Hourly 2D multi-offset GPR surveys were done along main axis of installations
- Hourly 3D ERT survey extended beyond the infiltration area
- Infiltration area was enclosed with overhead canopies and walls to minimize evapotranspiration (Figure 5)

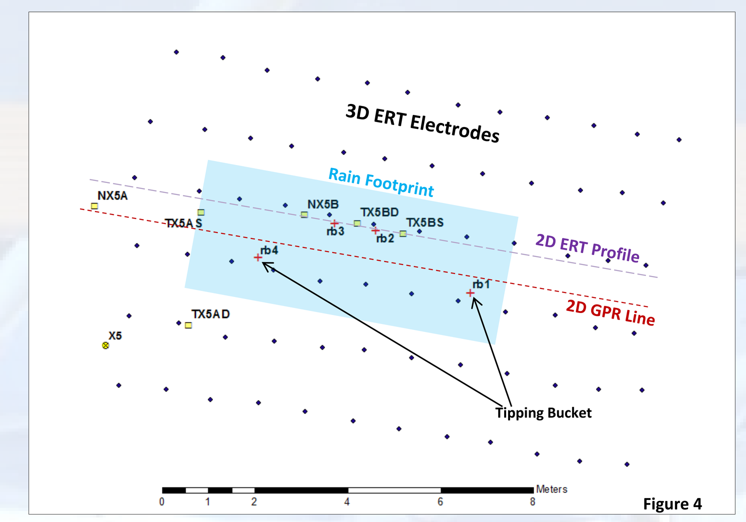

Figure 4

Test Duration

- Began August 1st at 11 am
  - ERT, GPR, moisture profiles, and soil surface temperature were taken every hour during the experiment and tensiometer measurements where logged every three minutes
- Continued rain at ~1 cm hr^{-1} until Aug. 2nd 8 am
  - The wetting portion of the experiment continued until both tension and moisture measurements appeared to reach steady-state
- Continued recovery measurements until Aug. 5th
  - Tension continued to be logged every 15 min and 2D GPR and soil moisture profiles were recorded for several days after rain had ceased

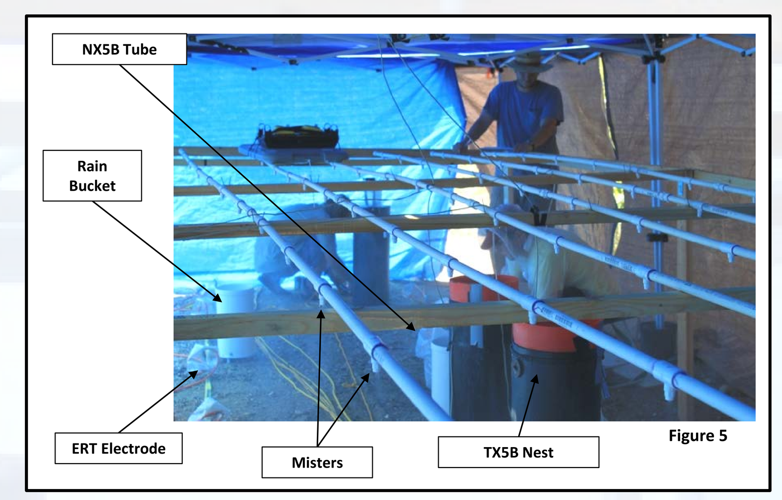

Figure 5

Observed Results of Infiltration

- Tension data were observed in real-time to track the wetting front
  - the shallowest TX5B tensiometer (AT-9; z = 0.37 m BLS) responds after ~1 hr; deepest tensiometer (AT-5 z = 1.29 m BLS) responds after ~6 hrs (Figure 6)
  - instantaneous wetting front velocity calculated from tension response shows a lower velocity at the depth of the sandy layer (~75 cm BLS) (Figure 7)
- Moisture content profiles were also used to track wetting front (figure 9)
  - moisture profiles show increased moisture retention (10% greater than above and below) at depth of sandy layer
  - measurements show similar response as tension although at greater depths moisture responds slower than tension (Figure 9), we attribute this to lateral heterogeneity in material properties and horizon depths
- Measurements of recovery over the following days show a slow gradual decrease in moisture and tension, although moisture measurements in the sandy zone remain high for several weeks
- Plots of tension and moisture measurements at paired depths show strong hysteresis (Figure 8)
  - These observations, however, may be strongly effected by lateral heterogeneity

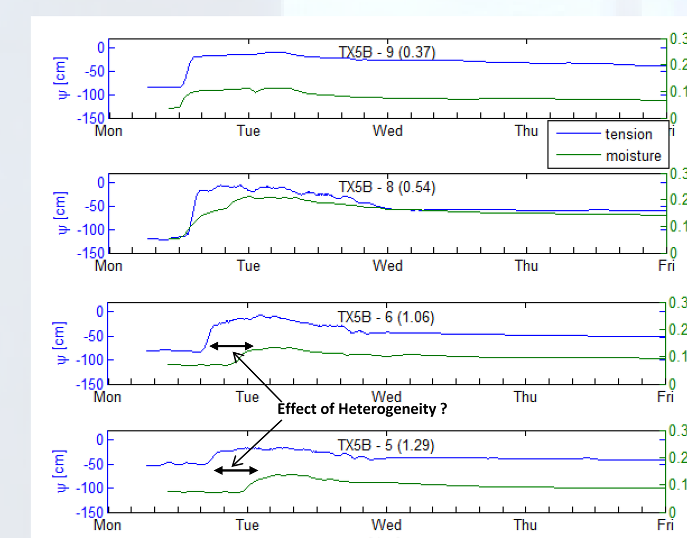

Figure 6

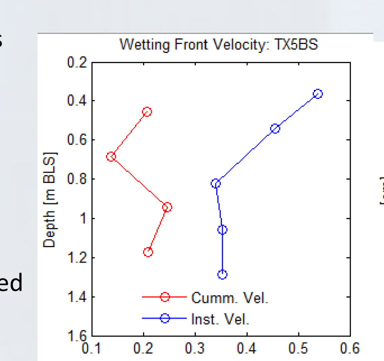

Figure 7

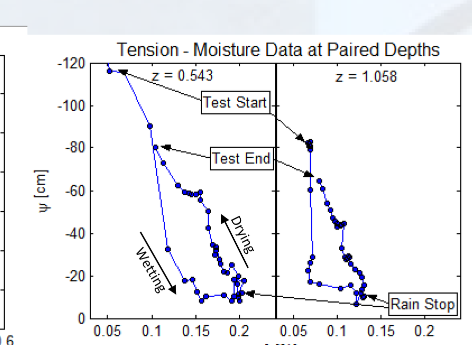

Figure 8

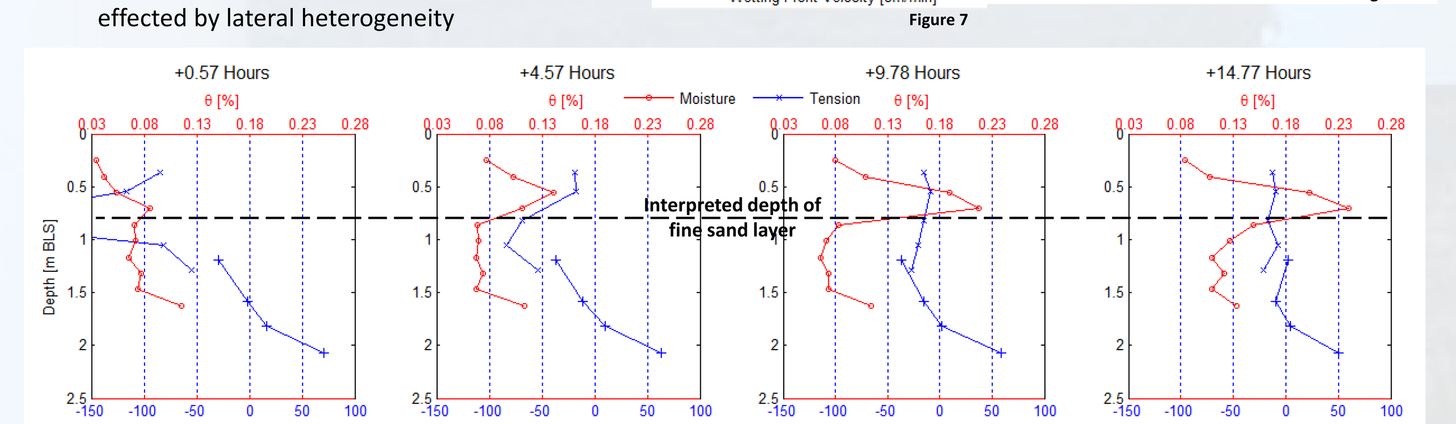

Figure 9

Geophysics Data

- 2D Multi-offset GPR and 3D ERT data were used to observe changes in electrical properties analogous to moisture
  - Resistivity (ρ) and EM velocity (v)
- 2D ERT was extracted from the 3D grid and processed using time-lapse inversion to obtain distribution of resistivity over time (Figure 10)
- 2D velocity analysis of GPR data and Topp[3] equation were used to estimate soil moisture distribution (Figure 11)
- Both data sets show a delay in the wetting front at the approximate depth of the sandy layer after about 12 hrs
- Both data sets show the effects of lateral heterogeneity caused a by dipping horizon (see Future Work)

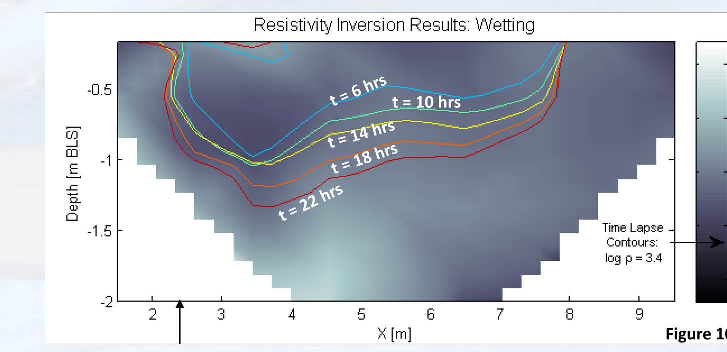

Figure 10

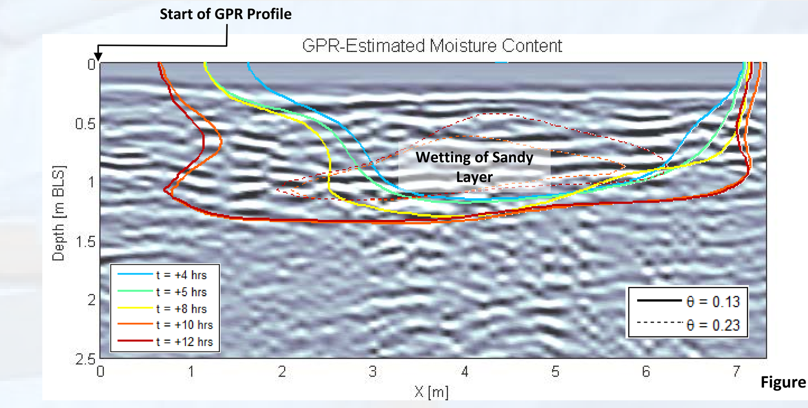

Figure 11

Hydrologic Modeling

Model Setup

- Based on core and geophysical data, a 4-layer model consisting of 3 materials (coarse sand/gravel, uniform coarse sand, fine sand) is initially used (Figure 13)
- Simulations are performed using HYDRUS 1D[2] and used to fit observed tension and moisture

Inversion Methods (In Progress)

- Monte-Carlo Approach (Figure 12; Table 2)
  - Randomly assign parameters from a range of possibilities
  - Track sum-squared error for each parameter set
  - Provides a distribution of "good-fit" parameter values
  - Issues with unrealistic parameter sets and non-unique solutions
  - Sensitivity to parameters must be considered
- Maximum Likelihood Approach
  - Provides automated method for finding ideal parameters
  - Issues with local minima and matrix conditioning

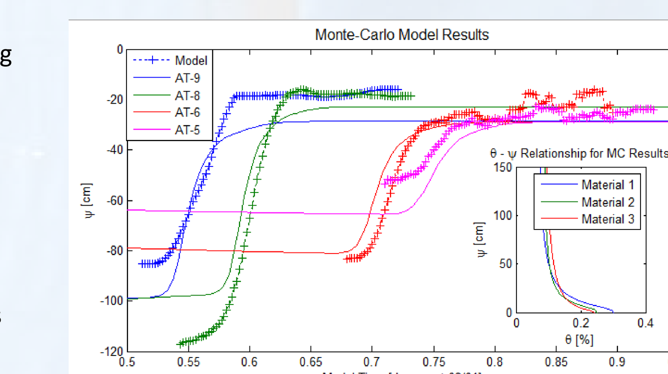

Figure 12

Monte-Carlo Parameter Results of Figure 12 — Table 3

	θ_R [%]	θ_S [%]	α [1/cm]	n [-]	K_{sat} [cm/s]
Material 1 (sand/gravel)	0.062	0.30	0.124	1.99	0.171
Material 2 (cs. sand)	0.083	0.25	0.141	2.09	0.129
Material 3 (fn. sand)	0.055	0.24	0.29	1.41	0.022

Future Work

2D Model

- Obvious heterogeneity observed can only be resolved using a higher-dimension model (Figure 13)
- A 2D saturated/unsaturated model should provide better results, especially with paired-depth tension-moisture data

Joint Inversion of Hydrologic and Geophysical Data

- Data from 2D hydrologic model can be used to predict soil moisture, which can be used to predict resistivity and GPR velocity distribution to match data

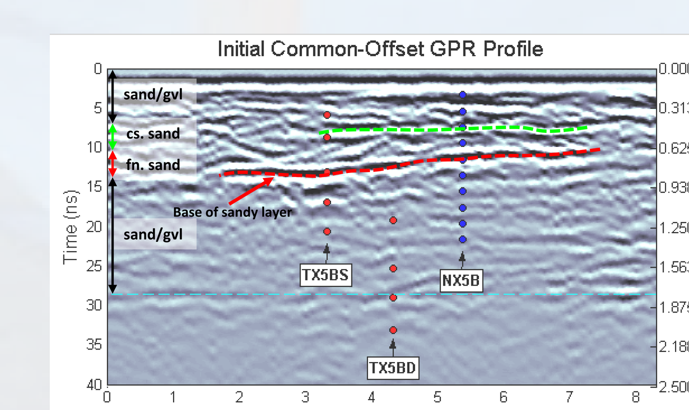

Figure 13

Acknowledgements

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